Scientia Horticulturae 240 (2018) 405–410

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

An approach to global warming effects on flowering and fruit set of olive trees growing under field conditions

María Benlloch-González[a,*], Rosa Sánchez-Lucas[b], Manuel Benlloch[a], Ricardo Fernández-Escobar[a]

[a] Departamento de Agronomía, Escuela Técnica Superior de Ingeniería Agronómica y de Montes, Universidad de Córdoba, Campus de Excelencia Internacional Agroalimentario, ceiA3, Ctra. Madrid-Cádiz, Km. 396, E-14071 Córdoba, Spain
[b] Departamento de Bioquímica y Biología Molecular, Escuela Técnica Superior de Ingeniería Agronómica y de Montes, Universidad de Córdoba, Campus de Excelencia Internacional Agroalimentario, ceiA3, Ctra. Madrid-Cádiz, Km. 396, E-14071 Córdoba, Spain

ARTICLE INFO

Keywords:
Climate change
High temperature
Olive flowering
Open top chamber (OTC)
Fruit set

ABSTRACT

The increase in air temperature associated to climate change is expected to affect olive (*Olea europaea* L.) tree fructification. To determine the potential effects of global warming on floral phenology and fruit set under field conditions, olive trees growing in a Mediterranean climate type area were subjected to warmer temperature than ambient by the use of temperature controlled Open-top-Chambers (OTCs). Each OTC, equipped with heating and ventilation devices, was able to maintain a day/night temperature gradient between the tree and the surrounding environment of 4 °C throughout the complete reproductive cycle of this species. After three years of study, the results obtained have shown that increasing temperature 4 °C above the actual ambient temperature may led to an advance of the date of flowering in the olive, an extent of the flowering period, an increase of pistil abortion, and a reduction in fruit set, conditions which may reduce yield.

1. Introduction

The Mediterranean Basin has been considered as one of the most vulnerable regions to climatic changes in the near future (Giorgi, 2006; Lionello, 2012). Climate experts have anticipated an increase in air temperature in the range of 2–5 °C (Giorgi, 2006; Giannakopoulos et al., 2009; Gualdi et al., 2013; IPCC, 2014). In addition, more frequent and extreme events such as drought periods and heat-waves will be observed in this region (Giorgi and Lionello, 2008; Tanasijevic et al., 2014). Temperature is a primary environmental factor controlling plant growth and development, so changes in seasonal temperatures can affect the biological processes of the reproductive cycle of Mediterranean crops, affecting crop production. The olive (*Olea europaea* L.) is one of the most emblematic crops in the Mediterranean Basin having a great economic, social and cultural impact. This species is widely spread and well adapted to the rustic conditions of the Mediterranean region, but a constant increase in ambient temperature may affect the phenology of this crop and, consequently, may reduce yield.

Floral phenology is a critical process in determining final yield. Olives flower on one-year-old wood and display two inflorescences per node or, exceptionally, directly at the shoot apex. The inflorescences contain a mixture of perfect (hermaphroditic) and imperfect (staminate) flowers. The former group contains well-developed stamens and pistil while in the latter a residual atrophied pistil is often visible in the center as a consequence of varying degrees of pistil abortion (Cuevas and Polito, 2004; Reale et al., 2006). Flower bud induction is manifested by July in the northern hemisphere (Fernández-Escobar et al., 1992), and floral differentiation is evident by March (Hartmann, 1951). Anthesis occurs by May. Shortly after anthesis, massive abscission of flowers and fruits occurs (Rallo and Fernández-Escobar, 1985). The remaining fruits usually persist on the tree until harvest, which takes place during the fall and winter (October-February) depending on the year and the cultivar. The olive tree exhibits a strong alternate bearing phenomenon.

Olive produces an abundant number of flowers but only a small percent (1–2%) of them set normal fruits that reach maturity (Martin, 1990; Lavee et al., 1996). This phenomenon is partly influenced by flower quality. It is not clear if warmer temperatures during pre-flowering and flowering phenophases could modify any morphological or developmental characteristics of the flower affecting its ability to set and form a fruit. Although it has been informed that environmental factors and cultural practices have a significant effect on floral quality (Hartmann, 1950; Uriu, 1953, 1960), there are not references related to temperature effect. Some studies have reported that poor N nutritional

* Corresponding author.
E-mail address: g72begom@uco.es (M. Benlloch-González).

https://doi.org/10.1016/j.scienta.2018.06.054
Received 8 May 2018; Received in revised form 13 June 2018; Accepted 14 June 2018
Available online 20 June 2018
0304-4238/ © 2018 Elsevier B.V. All rights reserved.

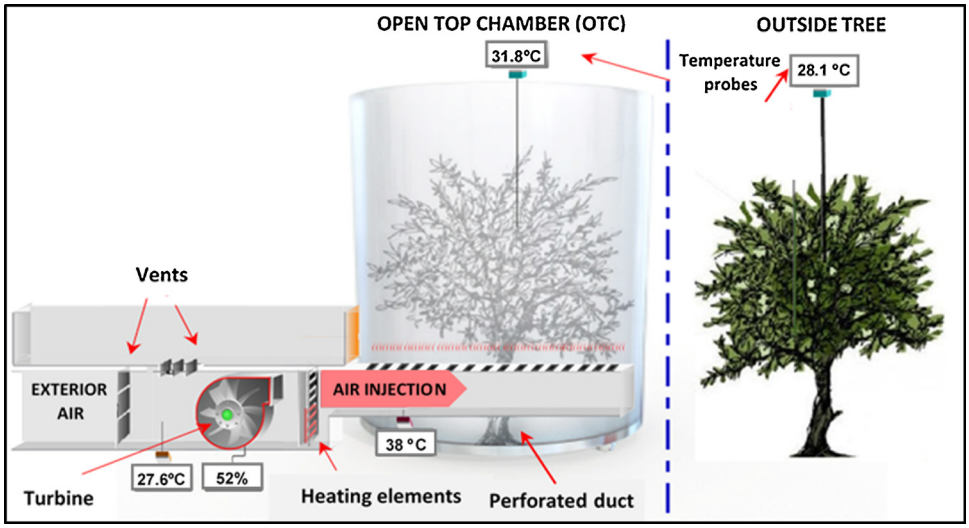

Fig. 1. Scheme of functioning of the Open Top Chamber.

status, low leaf-to-bud ratio and water deficit (Fernández-Escobar et al., 2008; Uriu, 1956, 1960; Cuevas and Polito, 2004; Reale et al., 2006; Rapoport et al., 2012) favor pistil abortion. There is also a cultivar-related tendency for producing imperfect flowers (Campbell, 1911; Morettini, 1950; Lavee et al., 1996; Rosati et al., 2011). On the other hand, the success of a flower to become a fruit not only depends on its quality but also on the pollination and fertilization processes. Studies that have analyzed the effect of temperature on pollen germination and pollen tube growth have reported that both are sensitive to elevated temperatures (Fernández-Escobar et al., 1983; Vuletin Selak et al., 2013). Constant temperatures above 33 °C after fertilization may affect fruit setting (Graniti et al., 2011) and subsequent fruit development (De Andrés Cantero, 2001).

Regional Climate Models and olive-pollen capture tramps have been used for long to predict olive floral timing in the Mediterranean region in the future. It seems that olive flowering date will be modified by the increase in air temperature (García-Mozo et al., 2010; Oteros et al., 2013): the development of floral structures will be completed faster leading to earlier flowering dates (Osborne et al., 2000; Giannakopoulos et al., 2009; Orlandi et al., 2010; Aguilera et al., 2015). However, long-term temperature field experiments are necessary to verify these results. Open top chambers (OTCs) are very useful tools for the simulation of global change under field conditions (Allen et al., 1992; Ceulemans and Mousseau, 1994; Norby et al., 1997). These systems are able to simulate real conditions of global warming including daily and seasonal fluctuations in weather. They allow trees to grow in the ground for several growing seasons avoiding the potential negative effects of container artefacts: root mechanic stress or the increase in soil temperature above ambient temperature due to containers overheating.

There is an actual tendency to compare floral phenology in olive orchards located in geographical regions differing in annual mean temperatures. But considering that floral events not only are governed by mean temperature but also by seasonal temperature fluctuations and the photoperiod along the different annual seasons, the results from these studies may lead to misunderstandings. These variables are difficult to be the same in different geographical regions because they partly depend on latitude and altitude.

The aim of this study was to determine under field conditions, in a Mediterranean climate area in which temperature and photoperiod fluctuations occur along the year, the effect of 4 °C increase in air temperature on olive floral phenology and fruit set. To reach this goal temperature controlled Open-Top-Chambers were used. This study is an approach to global warming effects on olive inflorescences characteristics, timing of the different events during flowering and fruit setting in the near future.

2. Material and methods

2.1. Plant material and growth conditions

'Picual' olive trees (*Olea europaea* L.) growing in a experimental farm of Campus de Rabanales, University of Córdoba, Spain (37°55′N 4°43′W) were used for the experiment. The orchard soil is classified as Calcic Luvisols with a clay-loam to clay texture, pH moderately alkaline (7–8), organic matter around 2%, and moderate to high cation exchange capacity (Del Campillo et al., 1993). The trees were planted in autumn 2009 spaced 8 x 6 m apart, with a drip irrigation system. Depending on the season, water was applied over five to six months during the dry season. The experiment was conducted from 2014 to 2017.

2.2. Experimental design and treatments

To perform this study sixteen trees were selected from the experimental farm. Trees were subjected to two temperature treatments, ambient temperature (AT) and 4 °C above ambient temperature (AT + 4 °C), along three consecutive years. The experimental plot was divided into four blocks containing each one two trees (replicates) per temperature treatments (AT vs. AT + 4 °C) which were randomly distributed. To maintain trees at 4 °C above ambient temperature, eight temperature-controlled Open Top Chambers (OTC), specifically designed for this study, were constructed around the trees (Fig. 1). Each OTC (hexagonal prism-shape), consisting of a steel frame covered by panels (panel size: 1.80 cm width x 3.60 cm height) of plastic film of high transparency (transmission: 90–85% of the solar photosynthetically active radiation), was equipped with heating and ventilation devices regulated by an automaton. In this way, a constant day/night temperature gradient between the tree and the surrounding environment of 4 °C was maintained throughout the complete reproductive cycle of this species.

The 4 °C thermal gradient was maintained by two mechanisms that operated independently. 1) A close circuit came into operation at night or under low solar radiation conditions to inject heat to the chamber. This circuit recirculates the air from the chamber through a turbined equipped with electric heating elements (Fig. 1). An automaton regulates the warm air flow by controlling the turbine speed and the number of electric heating elements which comes into operation. 2) During the day, under high solar radiation conditions, the excess of heat

accumulated in the chamber was partly eliminated by the injection of air from outside. The automaton selects one or another mechanism, acting on the closing or opening of two vents placed in the system (Fig. 1). The information processed by the automaton was provided by a temperature probe placed at the middle position of the tree canopy, both in control trees (TA) and those confined in the chambers (TA + 4 °C). The air injected into the chamber diffuses upwards along the tree from a 35 cm diameter duct, resting on the ground, provided with circular perforations (4 cm in diameter) (Fig. 1). The system provides a uniform air-flow of low flow once it reaches the branches of the tree.

2.3. Measurements

Fifteen uniformly distributed bearing shoots per tree were selected and tagged each spring. Shoot length was recorded at this time. Flowering was determined visiting periodically the trees from late February until the end of the flowering period, and recording the phenological stages described by Colbrant and Fabre (1975). The time of flowering was determined according to the method described by Fleckinger (1954). Flowering intensity per tree was determined using a visual scale from 0 (no flowering) to 3 (maximum flowering) at full bloom (FB).

The number of inflorescences and flowers per inflorescence were counted in each tagged shoot before anthesis. Fertile inflorescences and the number of perfect flowers per inflorescence were determined before petal fall. Fertile inflorescences were considered those with at least one perfect flower (Rallo and Fernández-Escobar, 1985). The number of fruits per tagged shoot was determined 40 days after full bloom (FB), when June drop is finished and fruit population is maintained until harvest (Rallo and Fernández-Escobar, 1985).

A fresh sample of four fully expanded leaves per tree was collected at noon at different times along the reproductive cycle of the olive to determine the leaf relative water content (RWC). Leaves were weighed, rehydrated over 24 h, and re-weighed, according to the procedure reported by Stocker (1929).

2.4. Statistical analysis

Analyses of variance were performed on the data using Statistix 9.0 software package (Analytical Software, Tallahassee, FL, USA). In all analyses, residual plots were generated to identify outliers and to confirm that variance was common and normally distributed. All percentage values were transformed using the arcsin of the square root before analysis. Non-parametric Friedman test was used to compare flowering intensity.

3. Results

The temperature gradient of around 4 °C between the air inside of the Open Top Chambers (OTC) and the surrounding environment, were maintained relatively constant from January to July of each year (Fig. 2). These results validate the treatments, indicating that the experimental trees were effectively subjected to different temperatures regimes.

Under these conditions, trees exposed to 4 °C above the ambient temperature (AT + 4 °C) initiated flowering between 18 and 24 days before than control trees, those exposed to the ambient temperature (AT), depending on the year (Fig. 3). Also, the flowering period and the full bloom period were between 5 and 7 days and 2–3 days longer, respectively. Flowering intensity, expressed as the amount of flowers per tree, estimated on a visual scale of 0 (non-flowering) to 3 (abundant flowering), did not show significant differences between temperature treatments (Fig. 4).

Flower quality was affected by warm temperatures (Table 1). The percentage of perfect flowers and fertile inflorescences significantly

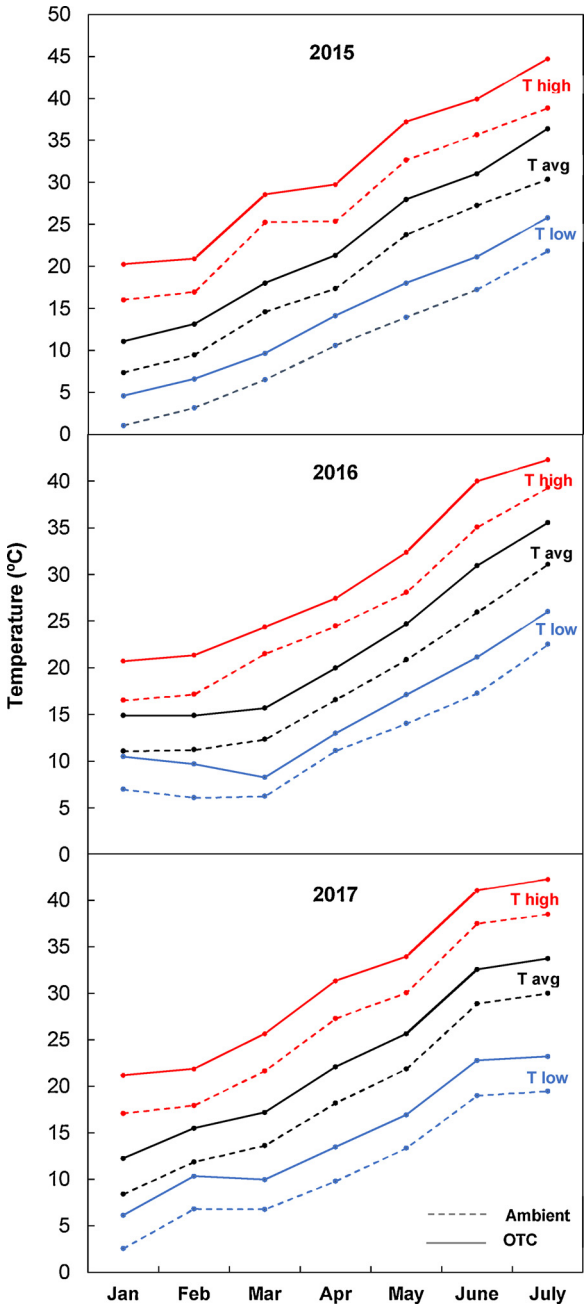

Fig. 2. Average monthly temperatures recorded from January to July during three consecutive years (T_{avg}). Dotted lines show ambient temperatures and the straight lines show OTC temperatures. T_{high} and T_{low} represents average high and low temperatures by month respectively.

decreased in AT + 4 °C trees in 2015 and 2016. No effect was observed in 2017. In 2015 pistil abortion was very intense even in control trees, which produced only 23.9% of fertile inflorescences and 5.9% of perfect flowers. On the contrary, in 2016 pistil abortion was very low, with 93.9% of fertile inflorescences and 56.4% of perfect flowers in AT trees. An intermediate behavior was observed in 2017.

Fruit set was also affected by the treatments. Expressing fruit set as the percentage of fruits per flower or per inflorescence, and also if it is expressed as fruit per cm of bearing shoot, fruit set significantly decrease in AT + 4 °C trees (Table 2). The only exception was in 2016, when fruit set was expressed as percent of fruits per perfect flowers.

The relative water content (RWC) of leaves was significantly lower in AT + 4 °C trees in winter 2015 and in spring 2016, and unaffected by

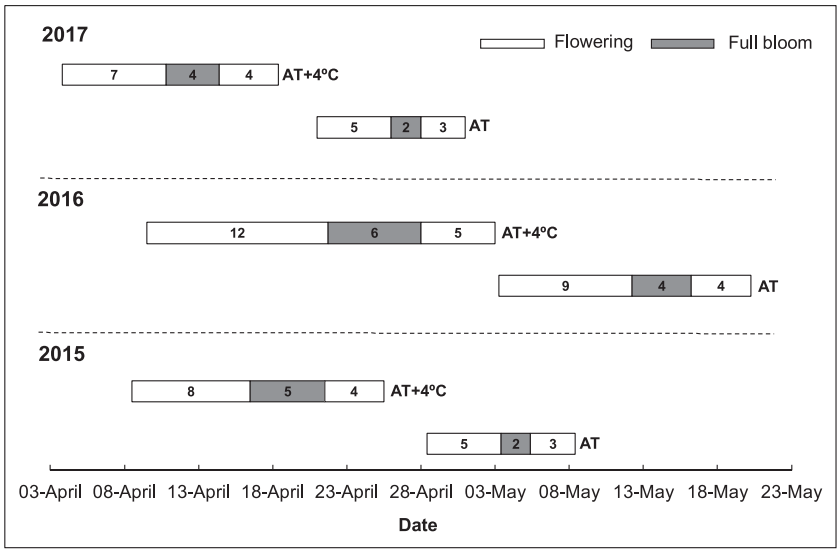

Fig. 3. Flowering period under ambient temperature (AT) and 4 °C above ambient temperature (AT + 4 °C) in three consecutive years. Inside of each bar from left to right it is represented the periods of time (days) from the start of flowering to the start of full bloom, from the start of full bloom to the end of full bloom, and from the end of full bloom to the end of flowering.

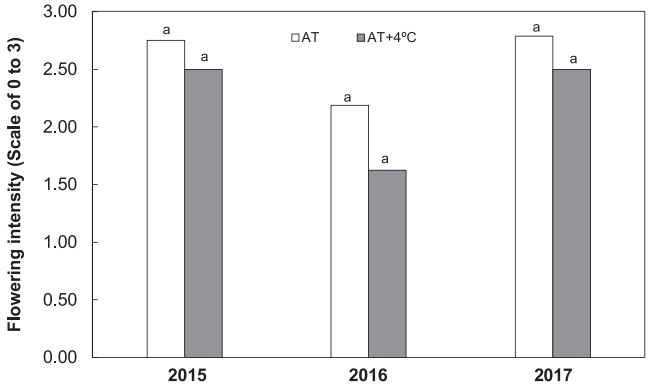

Fig. 4. Effect of a 4 °C increase in ambient temperature (AT vs. AT + 4 °C) on the amount of flowers produced by the trees in three consecutive years. Flowering rating: scale from 0 to 3 (none-very abundant flowering). Mean separation within each year by non-parametric Friedman test.

the treatments at these times in 2017 (Table 3). These results indicate that the AT + 4 °C trees was stressed around floral differentiation in 2015 and 2016 compared to control trees. During the summer, there were significant differences between treatments in all the years.

4. Discussion

The evaluation of the effect of global warming on the behavior of agricultural crops results of interest since an increase of temperature is expected in the near future (IPCC, 2014). For that reason, many works have been developed to study the responses of different crops to temperature. Usually, these studies have been realized contrasting the behavior of these crops in different environments (El Yaacoubi et al., 2014), that is, in different climatic regions, or developing models to predict the behavior of a particular crop (De Melo-Abreu et al., 2004). In the present work, we evaluated the effect of global warming on olive floral phenology and fruit set installing, under field conditions, temperature controlled open top chamber (OTC) systems, which maintain inside, almost constantly, 4 °C above the ambient temperature. That the system works is shown in Fig. 2. The advantage of this system is that allows observing the effect of an increase of temperature in each particular region. Data from the behavior of a particular crop in another region combines both the effect of an increase of temperature and also the other climatic particularities, which probably will not happen in another region.

Under the conditions of the experiment, it has been observed that an increase of 4 °C in air temperature induced an advance of the date of flowering. This effect was predicted to occur in southern Spain by Aerobiological studies and Regional Climatic Circulation Models (Galán et al., 2005; Osborne et al., 2000; Pérez-López et al., 2008; Giannakopoulos et al., 2009; Orlandi et al., 2014; Gabaldón-Leal et al., 2017). But our data also showed that these increase in air temperature extent the flowering period in about six days, when comparing with control trees growing at ambient temperatures. The flowering period is usually shortened when temperature increase during flowering and it is longer with lower temperatures (Rallo, 1997). A possible explanation to the extent of flowering in AT + 4 °C trees, could be that despite an

Table 1
Effect of a 4 ºC increase in ambient temperature (AT vs. AT + 4 ºC) on flower quality.

Temperature treatment	Flower quality[a,b]											
	2015				2016				2017			
	Flowers		Inflorescences		Flowers		Inflorescences		Flowers		Inflorescences	
	Total	Perfect (%)	Total	Fertile (%)	Total	Perfect (%)	Total	Fertile (%)	Total	Perfect (%)	Total	Fertile (%)
AT	110.5 a	5.9 a	10.5 a	23.9 a	113.4 a	56.4 a	9.1 a	93.9 a	137.1 a	11.5 a	11.8 a	40.4 a
AT + 4ºC	79.2 b	1.4 b	10.3 a	6.4 b	86.4 a	23.4 b	8.2 a	75.6 b	113.6 b	12.6 a	12.1 a	39.5 a
[c]*CV (%)*	22.3	39.7	8.2	32.9	23.7	5.9	22.7	5.5	11.1	48.1	8.4	36.8

[a] Means within each column followed by different letters are significantly different at $P \leq 0.05$ by F-test.
[b] Each data is the mean of eight trees and was obtained from 15 bearing shoots per tree.
[c] Coefficient of variation.

Table 2
Effect of a 4 ºC increase in ambient temperature (TA vs. TA + 4ºC) on fruit set determined 40 days after FB.

Temperature treatment	Fruit set[a,b]								
	2015			2016			2017		
	Fruit/cm	Flowers (%)	Inflorescences (%)	Fruit/cm	Flowers (%)	Inflorescences (%)	Fruit/cm	Flowers (%)	Inflorescences (%)
AT	0.17 a	14.5 a	31.1 a	0.70 a	10.5 a	75.6 a	0.35 a	26.8 a	59.4 a
AT + 4°C	0.01 b	1.1 b	1.9 b	0.23 b	10.7 a	34.0 b	0.16 b	8.1 b	23.8 b
[c]*CV (%)*	*64.9*	*52.6*	*66.8*	26.5	14.8	11.2	*19.8*	*17.3*	*17.5*

[a] Means within each column followed by different letters are significantly different at $P \leq 0.001$ by F-test.
[b] Expressed as number of fruits per cm of bearing shoot or as the percentage of perfect flowers or fertile inflorescence. Each data is the mean of eight trees, and was obtained from 15 bearing shoots per tree.
[c] Coefficient of variation.

Table 3
Effect of a 4 °C increase in ambient temperature (TA vs. TA + 4 °C) on leaf relative water content (RWC).

Temperature treatment	Leaf RWC (%)[a]								
	2015			2016			2017		
	Winter	Spring	Summer	Winter	Spring	Summer	Winter	Spring	Summer
AT	93.2 a	–	89.3 a	89.1 a	92.6 a	87.8 a	88.9 a	90.7 a	90.6 a
AT + 4°C	89.6 b	–	86.9 b	88.4 a	90.5 b	86.1 b	88.2 a	91.0 a	89.4 b
[b]*CV*	*1.3*	–	*1.37*	*1.88*	*0.8*	*1.26*	*1.43*	*1.08*	*0.78*

[a] Means within each column followed by different letters are significantly different at $P \leq 0.05$ by F-test.
[b] Coefficient of Variation.

increase of temperature of 4 °C, the advancement of the date of flowering to the beginning of April can make that flowering occurs with lower temperatures than flowering in control trees. However, according to the data recorded in Fig. 2, the average temperatures in April inside the OTCs were similar to external May temperatures, when control trees bloomed. We have no explanation for this disagreement, unless than other factors may affect the extension of the flowering period, since this effect was observed in all the years.

Percentage of perfect flowers is important for olive yield. This characteristic has an important varietal component, but it is influenced by environmental conditions, particularly by water deficit during flower differentiation (Uriu, 1960; Hartmann and Panetssos, 1961; Rapoport et al., 2012). In our experiment, pistil abortion occurs in 2015 and 2017 in both AT + 4 °C trees and AT trees, probably because the low rainfall at the end of the winter in both years. Very low abortion was observed in AT tree in 2016, when rainfall was higher than in the other years. But in both 2015 and 2016, pistil abortion was significantly higher in AT + 4 °C trees, and no significant differences were observed in 2017. The relative water content (RWC) of leaves was significantly different in AT and AT + 4 °C trees in winter 2015 and spring 2016, suggesting a different water status of these trees in dates close to floral differentiation, which may explain the differences observed in pistil abortion in these years. No differences in water status were observed in winter or spring of 2017 between AT and AT + 4 °C trees, which may explain the lack of differences in pistil abortion in this year.

In addition to the reduction of perfect flowers and fertile inflorescences in AT + 4 °C trees, characteristics which may reduce yield, fruit set was also significantly reduced in these trees. The high temperature treatment may influence flower fertilization, resulting in a poor fruit setting. In other species, temperature affects stigma receptivity (Burgos et al., 1991), ovule longevity (Postweiler et al., 1985) and pollen tube growth (Lewis, 1942; Williams, 1970). In the olive, the optimum temperature for pollen germination and pollen tube growth has been observed to be 25 °C. When temperature is above 30 °C, these processes fail affecting fruit setting (Fernández-Escobar et al., 1983; Cuevas et al., 1994). Temperatures above 30 °C have been reached during the pollination period under the experimental conditions of this study, and may have limited flower fertilization and fruit set. Cross-pollination, that is, the pollination with pollen of a different cultivar, allow a greater pollen germination and pollen tube growth at higher temperatures than the own pollen (Fernández-Escobar et al., 1983), suggesting a higher fruit set under these conditions. In fact, the need for cross-pollination in the olive has been reported in areas of Israel, Argentina or Mexico (Rallo and Cuevas, 2017), where temperatures during olive flowering are usually higher than in southern Spain. Results suggest that, under an increase of temperature during flowering, cross-pollination may be a technique to increase fruit set and, consequently, yield.

In conclusion, increasing temperature 4 °C above the actual ambient temperature may led to an advance of the date of flowering in the olive, an extent of the flowering period, an increase of pistil abortion, and a reduction in fruit set, conditions which may reduce yield. These results suggest that it could be necessary to reduce trees stress during the winter, probably providing irrigation water during floral differentiation or by prolong the irrigation period during the autumn and winter. Also, cross-pollination could be necessary to guarantee a normal fruit set and productivity.

Acknowledgments

This study has been supported by Consejería de Economía y Conocimiento de la Junta de Andalucía “Incentivos a Proyectos de Investigación de Excelencia” (Ref. AGR/7152) and co-financed by Plan Propio de Investigación de la Universidad de Córdoba and Programa Operativo de fondos FEDER Andalucía. We would like also to thanks Inmaculada Garcia Martos and Regla Paloma Ortega Peralta for their help in field data collection.

References

Aguilera, F., Fornaciari, M., Ruiz-Valenzuela, L., Galán, C., Msallem, M., Ben Dhiab, A., Díaz de la Guardia, C., Trigo, M.M., Bonofiglio, T., Orlandi, F., 2015. Phenological models to predict the main flowering phases of olive (Olea europaea L.) along a latitudinal and longitudinal gradient across the Mediterranean region. Int. J. Biometeorol. 59, 629–641.

Allen Jr, L.H., Drake, B.G., Rogers, H.H., Shinn, J.H., 1992. Field techniques for exposure of plants and ecosystems to elevated CO2 and other trace gases. Crit. Rev. Plant Sci. 11, 85–119.
Burgos, L., Egea, J., Dicenta, F., 1991. Effective pollination period in apricot (Prunus armeniacaL.) varieties. Ann. Appl. Biol. 119, 533–539.
Campbell, C., 1911. L'aborto fiorale nell'olivo. L'Italia Agricola 16.
Ceulemans, R., Mousseau, M., 1994. Tansley review no. 71: effects of elevated atmospheric CO2 on woody plants. New Phytol. 127, 425–446.
Colbrant, P., Fabre, P., 1975. Stades reperes de l'oliver. In: Maillard, R. (Ed.), L'oliver. INVUFLEC, Paris, pp. 24–25.
Cuevas, J., Polito, V.S., 2004. The role of staminate flowers in the breeding system of Olea europaea (Oleaceae): an andromonoecious, wind-pollinated taxon. Ann. Bot. 93, 547–553.
Cuevas, J., Rallo, L., Rapoport, H.F., 1994. Crop load effects on floral quality in olive. Sci. Hortic. 59, 123–130.
De Andrés Cantero, F., 2001. Enfermendades y plagas del olivo. Riquelme y Vargas Ediciones. Madrid, Spain. .
De Melo-Abreu, J.P., Barranco, D., Cordeiro, A.M., Tous, J., Rogado, B.M., Villalobos, F.J., 2004. Modelling olive flowering date using chilling for dormancy release and thermal time. Agric. For. Meteorol. 125, 121–127.
Del Campillo, M.C., Delgado, A., Giménez, A., Torrent, J., 1993. Estudio Edafológico de la Finca Rabanales (Córdoba). Departamento de Ciencias y Recursos Agrícolas y Forestales. Universidad de Córdoba, Córdoba. Spain.
El Yaacoubi, A., Malagi, G., Oukabli, A., Hafidi, M., Legave, J.M., 2014. Global warming impact on floral phenology of fruit tree species in Mediterranean region. Sci. Hortic. 180, 243–253.
Fernández-Escobar, R., Gómez-Valledor, G., Rallo, L., 1983. Influence of pistil extract and temperature on in vitro pollen germination and pollen tube growth of olive cultivars. J. Hortic. Sci. 58, 219–227.
Fernández-Escobar, R., Benlloch, M., Navarro, C., Martin, G.C., 1992. The time of floral induction in the olive. J. Am. Soc. Hortic. Sci. 117, 304–307.
Fernández-Escobar, R., Ortiz-Urquiza, A., Prado, M., Rapoport, H.F., 2008. Nitrogen status influence on olive tree flower quality and ovule longevity. Environ. Exp. Bot. 64, 113–119.
Fleckinger, J., 1954. Observations recents sur l´ecologie du pommier a cidre VIII Congress International Botanique. pp. 10.
Gabaldón-Leal, C., Ruiz-Ramos, M., de la Rosa, R., León, L., Belaj, A., Rodríguez, A., Santos, C., Lorite, I.J., 2017. Impact of changes in mean and extreme temperatures caused by climate change on olive flowering in southern Spain. Inter. J. Climatol. 37, 949–957.
Galán, C., Garcia-Mozo, H., Vazquez, L., Ruiz-Valenzuela, L., Díaz de laGuardia, C., Trigo-Perez, M., 2005. Heat requirement for the onset of the Olea europaea L. pollen season in several places of Andalusia region and the effect of the expected future climate change. Int. J. Biometeorol. 49, 184–188.
García-Mozo, H., Mestre, A., Galán, C., 2010. Phenological trends in southern Spain: a response to climate change. Agric. For. Meteorol. 150, 575–580.
Giannakopoulos, C., Le Sager, P., Bindi, M., Moriondo, M., Kostopoulou, E., Goodess, C.M., 2009. Climatic changes and associated impacts in the Mediterranean resulting from a 2 ºC global warming. Global Planet Change 68, 209–224.
Giorgi, F., 2006. Climate change hot-spots. Geophys. Res. Lett. 33 L08707.
Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. Global Planet Change 63, 90–104.
Graniti, A., Faedda, R., Cacciola, S.O., San, Magnanodi, Lio, G., 2011. Olive diseases in a changing ecosystem. En. In: Schena, L., Agosteo, G.E., Cacciola, S.O. (Eds.), Olive Diseases and Disorders. Transworld Research Newtwork, Trivandrum, Kerala, India, pp. 403–433.
Gualdi, S., Somot, S., Li, L., Artale, V., Adani, M., Bellucci, A., Braun, A., Calmanti, S., Carillo, A., Dell'Aquila, A., Déqué, M., Ruti, C., Sanna, A., Sannino, G., Scoccimarro, E., Sevault, F., Navarra, A., 2013. The CIRCE simulations: regional climate change projections with realistic representation of the Mediterranean Sea. Bull. Am. Meteor. Soc. 94, 65–81.
Hartmann, H.T., 1950. Olive flower bud formation. Calif. Agric. 4, 4–16.
Hartmann, H.T., 1951. Time of floral differentiation of the olive in California. Bet. Gaz. 112, 323–327.
Hartmann, H., Panetssos, C., 1961. Effect of soil moisture deficiency during floral development on the fruitfulness in olives. Proc. Am. Sci. 78, 209–217.
IPCC (Intergovernmental Panel on Climate Change), 2014. In: Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, pp. 151 Core Writing Team.
Lavee, S., Rallo, L., Rapoport, H.F., Troncoso, A., 1996. The floral biology of the olive: effect of flower number, type and distribution on fruitset. Sci. Hortic. 66, 149–158.
Lewis, D., 1942. The physiology of incompatibility in plants. I. Effect of temperature. Proceedings of the Royal Society, London 131, 13–26.
Lionello, P., 2012. The Climate of the Mediterranean Region: From the Past to the Future. Elsevier, New York.
Martin, G.C., 1990. Olive flower and fruit production dynamics. Acta Hortic. 286, 141–153.
Morettini, A., 1950. Ulteriore contributo allo studio dell'aborto dell'ovario nel fiore dell'olivo. Ann. Sper. Agric. 5, 309–329.
Norby, R.J., Edwards, N.T., Riggs, J.S., Abner, C.H., Wullschleger, S.D., Gunderson, C.A., 1997. Temperature-controlled open-top chambers for global change research. Global Change Biol. 3, 259–267.
Orlandi, F., García-Mozo, H., Galán, C., Romano, B., Díaz de la Guardia, C., Ruíz, L., Trigo, M.M., Domínguez-Vilches, E., Fornaciari, M., 2010. Spring influences on olive flowering and threshold temperatures related to reproductive structure formation. HortScience 45, 1052–1057.
Orlandi, F., Garcia-Mozo, H., Dhiab, A.B., Galán, C., Msallem, M., Fornaciari, M., 2014. Olive tree phenology and climate variations in the Mediterranean area over the last two decades. Theor. Appl. Climatol. 115, 207–218.
Osborne, C.P., Chuine, I., Viner, D., Woodward, F.I., 2000. Olive phenology as sensitive indicator of future climatic warming in the Mediterranean. Plant Cell Environ. 23, 701–710.
Oteros, J., García-Mozo, H., Hervás-Martínez, C., Galán, C., 2013. Year clustering analysis for modelling olive flowering phenology. Int. J. Biomet. 57, 545–555.
Pérez-López, D., Ribas, F., Moriana, A., Rapoport, H.F., De Juan, A., 2008. Influence of temperature on the growth and development of olive (Olea europaea L) trees. J. Hortic. Sci. Biotechnol. 83, 171–176.
Postweiler, K., Stösser, R., Anvari, S.F., 1985. The effect of different temperatures on the viability of ovules in cherries. Scientia Hort. 25, 235–239.
Rallo, L., 1997. Fructificación y producción. In: Barranco, D., Fernández Escobar, D., Rallo, L. (Eds.), El Cultivo del Olivo. Junta de Andalucía, Andalucía, España, pp. 107–136.
Rallo, L., Cuevas, J., 2017. Fructificación y Producción. In: In: Barranco, D., Fernández-Escobar, R., Rallo, L. (Eds.), El Cultivo del Olivo Vol. 5. Mundi-Prensa, Madrid, pp. 147–184.
Rallo, L., Fernández-Escobar, R., 1985. Influence of cultivar and flower thinning within the inflorescence on competition among olive fruit. J. Am. Soc. Hortic. Sci. 110, 303–308.
Rapoport, H.F., Hammami, S.B.M., Martins, P., Pérez-Priego, O., Orgaz, F., 2012. Influence of water deficits at different times during olive tree inflorescence and flower development. Environ. Exp. Bot. 77, 227–233.
Reale, L., Sgromo, C., Bonofiglio, T., Orlandi, F., Fornaciari, M., Ferranti, F., Romano, B., 2006. Reproductive biology of olive (Olea europaea L.) DOP Umbria cultivars. Sex Plant Reprod. 19, 151–161.
Rosati, A., Caporali, S., Paoletti, A., Famiani, F., 2011. Pistil abortion is related to ovary mass in olive (*Olea europaea* L.). Sci. Hortic. 127, 515–519.
Stocker, O., 1929. Das Wasserdefizit von Gefässpflanzen in verschiedenen Klimazonen. Planta 7, 382–387.
Tanasijevic, L., Todorovic, M., Pereira, L.S., Pizzigalli, C., Lionello, P., 2014. Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region. Agric. Water Manage. 144, 54–68.
Uriu, K., 1953. Pistil Abortion in the Olive (*Olea europaea* L.) as Influenced by Certain Physiological Conditions. PhD Thesis. University of California, USA.
Uriu, K., 1956. Pistil abortion in the olive. Calif. Agric. 10, 13–14.
Uriu, K., 1960. Periods of pistil abortion in the development of the olive flower. Proc. Am. Soc. Hortic. Sci. 73, 194–202.
Vuletin Selak, G., Perica, S., Ban, S.G., Poljak, M., 2013. The effect of temperature and genotype on pollen performance in olive (Olea europaea L.). Sci. Hortic. 156, 38–46.
Williams, R.R., 1970. Factors affecting pollination in fruit trees. In: Luckwill, L.C., Cutting, C.V. (Eds.), Physiology of Tree Crops. Academic Press, London, UK, pp. 193–207.